Physics Letters B 741 (2015) 55–60

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Parity violation in pre-inflationary bounce

Yu-Tong Wang [a,*], Yun-Song Piao [a,b]

[a] School of Physics, University of Chinese Academy of Sciences, Beijing 100049, PR China
[b] State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, PR China

ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form 4 December 2014
Accepted 4 December 2014
Available online 10 December 2014
Editor: J. Hisano

ABSTRACT

The power suppression on large scale in the CMB TT-mode power spectrum might imply the occurrence of a pre-inflationary bounce. We calculate the circularly polarized gravitational wave, leaded by the gravitational Chern–Simons term universally appearing in particle physics and string theory, in the inflation model with the pre-inflationary bounce. The circularly polarized gravitational wave will induce TB- and EB-mode correlations at CMB last scatting surface. We find that if the pre-inflationary bounce actually occurs, the TB- and EB-mode correlations on large scale will be enhanced, while the BB-mode correlation on corresponding scales is suppressed.

1. Introduction

Recently, the Planck Collaboration has reported a power deficit in the CMB TT power spectrum on largest scale [1,2], which also was found in WMAP data, and is not concordant with the Planck best-fit model. Its statistical significance is about 3σ. In addition, the Planck Collaboration has also reported a hemispherical power asymmetry in CMB at low-l [2], which conformed a similar observation of WMAP [3,4], see also [5,6].

These large-scale anomalies might be a hint of the pre-inflationary physics relevant to the initial singularity [7,8]. In Refs. [7,9–12], the pre-inflationary universe is in a contracting phase and after the bounce the universe begins to inflate. In Refs. [13–15], the pre-inflationary universe is in a superinflationary phase, see also [16] for the case with $\epsilon \ll -1$, which is similar to the emergent universe scenario [17]. The above pre-inflationary evolutions generally will generate a large-scale cutoff in the primordial power spectrum, which may naturally suppress the CMB TT power spectrum at low-l, see, e.g., [11,13] for the details. In such scenarios, it is generally required that the slow-roll inflation lasts for just the minimal number of efoldings, i.e.just enough inflation [18], and thus the power deficit at low-l may be attributed to the evolution of the pre-inflationary non-slow-roll background, e.g. see Ref. [19] for a discussion on the pre-inflationary expanding phase, and also earlier Refs. [20] and [21]. See, e.g., [13,22–25] for some stringy embeddings.

The measure of large-scale E- and B-mode polarizations [26,27] will help to provide a unambiguous test for the pre-inflationary evolution. The scalar perturbation contributes the TT-, TE- and EE-mode correlations in CMB, while the gravitational wave (GW) contributes the BB-mode correlation besides the TT-, TE- and EE-mode correlations.

However, if the gravity is chiral, we might have other channels to test the evolution of pre-inflationary universe. The gravitational Chern–Simons (gCS) term, motivated by the anomaly cancellation in particle physics and string theory [28,29], is parity-violating, see Ref. [30] for a review, which will produce a difference between the amplitudes of right-handed and left-handed GWs [31–33]. The primordial circularly polarized GW will induce TB- and EB-mode correlations at CMB last scatting surface [34–38].

The TB and EB correlations may be also brought by the electromagnetic CS term, e.g. [39–41], which affects the CMB polarizations after the photon decoupling, e.g. [42], see [43] for the analysis with latest data. As a result, the shape of TB-mode power spectrum is generally the same with that of TE-mode power spectrum. Thus such a power spectrum lead by electromagnetic CS term is different from a power spectrum lead by gravitational CS term, see, e.g., [36].

In conventional slow-roll inflation scenario, the circular polarization of primordial GW from the gCS term is negligible [44,45]. Thus the primordial TB and EB correlations in CMB is unseen [34,36]. However, the significant circular polarization may be created in a string-inspired inflationary model with the GB term [46]. In this sense, it seems that the TB- and EB-mode correlations recording the chirality of primordial gravity might also encode the information of the evolution of primordial universe.

* Corresponding author.
E-mail addresses: wangyutong12@mails.ucas.ac.cn (Y.-T. Wang), yspiao@ucas.ac.cn (Y.-S. Piao).

http://dx.doi.org/10.1016/j.physletb.2014.12.011

The pre-inflationary bounce [7,11] not only may account for the CMB anomalies at large scale, but also avoid the initial singularity problem of inflationary universe. Thus it is interesting to investigate the TB- and EB-mode correlations in such a scenario.

Here, we will calculate the circularly polarized GW leaded by the gCS term in the inflation model with the pre-inflationary bounce. We find that if the pre-inflationary bounce actually occurs, the TB- and EB-mode correlations on large scale will be enhanced, while the BB-mode correlation on corresponding scales is suppressed.

2. Pre-inflationary gravitational wave

The gravitation action including the gCS term is

$$S = S_{Einstein} + \int (-g)^{1/2} d^4x \frac{f(\phi)}{8} R \wedge R, \tag{1}$$

in which ϕ is identified as the inflaton in the slow-roll inflation or the background field in the pre-inflationary evolution.

The gCS term only affects the tensor perturbation, but does not affect the scalar perturbation and the evolution of background, e.g. [31]. The tensor perturbation h_{ij} obeys $\delta^{ij} h_{ij} = 0$ and $\partial_i h^{ij} = 0$, and its action is

$$S_2 = \frac{1}{8} \int d\eta d^3x \big[a^2 M_P^2 \big({h_{ij}}'^2 - (\partial h_{ij})^2\big) - f' \epsilon^{ijk} \big(h_i^{q\prime} (\partial_j h_{kq})' - \partial^r h_i^q \partial_j \partial_r h_{kq}\big)\big], \tag{2}$$

where ϵ^{ijk} is the Levi-Civita symbol, and $'$ is the derivative with respect to $\eta = \int dt/a$.

Here, the universe is initially in a contracting phase and after the bounce it is in the inflationary phase. To investigate the evolution of h_{ij}, we will adopt an instantaneous matching between both phases [7,11], i.e.

$$a \simeq a_* (1 - 2\mathcal{H}_* \eta)^{1/2} \quad \text{for contracting phase}, \\ \frac{a_*}{1 - \mathcal{H}_* \eta} \quad \text{for inflationary phase}, \tag{3}$$

respectively, where $\mathcal{H}_*$ sets the slow-roll inflationary scale by $H_{inf} = H_* = \mathcal{H}_*/a_*$. Here, the pre-inflationary contraction is a kinetic-dominated phase, see Ref. [11] for a detailed model. In this mode, the ghost-free bounce may be implemented in Einstein gravity, e.g. [47–50]. In addition, the bounce can also be realized with modified gravity [51–53]. Actually, lots of the bounce mechanisms have been argued, see [54,55] for reviews and references. Generally the perturbation may continuously pass through the bounce, and its spectrum is insensitive with respect to the implementing detail of the bounce, e.g. [56]. See also [57] for other case.

We, following Ref. [44], define the left-handed and right-handed circular polarization modes h_s with the circular polarization tensor ${p^s}_{ij}$, and expand h_{ij} as

$$h_{ij}(t, \mathbf{x}) = \sum_{s=L,R} \int \frac{d^3\mathbf{k}}{(2\pi)^3} h_s(t, \mathbf{k}) p_{ij}^{(s)} e^{i\mathbf{k}\cdot\mathbf{x}}, \tag{4}$$

where $ik_q \epsilon^{rqj} p_{ij}^{(s)} = k\lambda_s p_i^{r(s)}$, and the modes with $\lambda_{R,L} = 1, -1$ are called as the right-handed mode and the left-handed mode, respectively.

Thus with (2), the equation of $h_s(t, \mathbf{k})$ is

$$v_{sk}'' + \left(k^2 - \frac{{z_s}''}{z_s}\right) v_{sk} = 0, \tag{5}$$

where $v_{sk} \equiv z_s h_s$, and $z_s = a(1 - \frac{\lambda_s k}{a^2} \frac{f'}{M_P^2})^{1/2}$. Here, $f = \alpha \frac{\phi}{M_P}$ and α is a parameter determined by the potential fundamental theory. Thus z_s equals to

$$z_s = a\sqrt{1 - \lambda_s \Theta\left(-\frac{k}{\mathcal{H}}\right)}, \tag{6}$$

where $\Theta = \frac{\alpha H^2 \sqrt{2\epsilon}}{M_P^2}$ and $\epsilon = -\dot{H}/H^2$. When $k^2 \simeq z_s''/z_s$, the perturbation mode is leaving the horizon. When $k^2 \ll z_s''/z_s$, the solution of h_s given by Eq. (5) is

$$h_s \sim C \quad \text{is constant mode} \tag{7}$$

$$\text{or } D \int \frac{d\eta}{z_s^2} \quad \text{is decaying mode.} \tag{8}$$

2.1. The unpolarized gravitational wave

When the gCS term is negligible, which implies $z_s = a$, both h_R and h_L will be equal and $v_{Rk} = v_{Lk} = v_k$. We firstly investigate this unpolarized case.

When $k^2 \gg \frac{a''}{a}$, i.e. the perturbation is deeply inside the horizon, v_k oscillates with a constant amplitude,

$$v_k \sim \frac{1}{\sqrt{2k}} e^{-ik\eta}. \tag{9}$$

When $k^2 \ll \frac{a''}{a}$, i.e. the perturbation is far outside the horizon, in the pre-inflationary contracting phase, the solution of Eq. (5) is given by

$$v_k = \sqrt{\frac{\pi}{4}\left(x + \frac{k}{\mathcal{H}_*}\right)} H_0^{(1)}\left(x + \frac{k}{\mathcal{H}_*}\right), \tag{10}$$

where $x = k/\mathcal{H}_* - k\eta$, $H_0^{(1)}$ is the 0th order Hankel function of the first kind. While in the slow-roll inflationary phase the solution of Eq. (5) is

$$v_k = x^{1/2} \big[C_1 H_{3/2}^{(1)}(x) + C_2 H_{3/2}^{(2)}(x)\big], \tag{11}$$

where $H_{3/2}^{(1)}$ and $H_{3/2}^{(2)}$ are the (3/2)th-order Hankel function of the first kind and the second kind, respectively, the parameters C_1 and C_2 are only dependent on k.

The continuity of h_s around the bounce gives C_1 and C_2. Thus the GW spectrum is

$$\mathcal{P}_T = \sum_{s=L,R} \mathcal{P}_{T,s} = \mathcal{P}_{T,inf} \frac{2k}{\pi \mathcal{H}_0} |C_1 - C_2|^2, \tag{12}$$

where $\mathcal{P}_{T,s} = \frac{k^3}{\pi^2} |h_s/a|^2$, and $\mathcal{P}_{T,inf} = \frac{2H_{inf}^2}{\pi^2 M_P^2}$ is that of the slow-roll inflation. We plot $\mathcal{P}_T(k)$ in Fig. 1, $\mathcal{P}_T(k)$ is almost scale-invariant for $k > \mathcal{H}_*$, since the corresponding modes are produced in slow-roll inflationary phase, while for $k < \mathcal{H}_*$ it gets a cutoff. The shape of $\mathcal{P}_T(k)$ is the same with that of the scalar spectrum in Ref. [11].

When $k \ll \mathcal{H}_*$, we have approximately

$$\mathcal{P}_T^{k<\mathcal{H}_*} \sim \left(2 + \ln \frac{4\mathcal{H}_0}{k}\right)^2 \frac{k^3}{\mathcal{H}_0^3} \mathcal{P}_{T,inf}, \tag{13}$$

which is the usual output of original Pre-big bang scenario [58,59], i.e. $n_T \simeq 3$. While for $k \gg \mathcal{H}_*$, we have approximately

$$\mathcal{P}_T^{k>\mathcal{H}_*} \sim \left(1 + \frac{\mathcal{H}_*}{4k} \sin \frac{2k}{\mathcal{H}_*}\right) \mathcal{P}_{T,inf}, \tag{14}$$

which is almost scale-invariant, but with a decaying oscillation. The result is consistent with the solid line in Fig. 1.

2.2. The circularly polarized gravitational wave

When the gCS term is not negligible, it will produce a difference between the amplitudes of h_R and h_L. Here, to quantify this chirality, we define a chiral parameter $\Delta\chi$ as $\mathcal{P}_{T,s} = (1-\lambda_s\Delta\chi)\mathcal{P}_T/2$, in which $-1 \le \Delta\chi \le 1$ reflects the magnitude of parity violation of primordial GW. This definition equals to that in [34,36], also [46] but with inverse sign.

When $k > \mathcal{H}_*$, the modes are produced in the slow-roll inflationary phase. In slow-roll inflation, the power spectrum of h_s is, Ref. [44],

$$\mathcal{P}_{T,s}^{k>\mathcal{H}_*} \simeq \frac{H_{inf}^2}{\pi^2 M_P^2}\left(1-\lambda_s\frac{\pi\Theta}{2}\right), \tag{15}$$

where the terms with higher order Θ are neglected. With Eq. (15), we have

$$\Delta\chi_{inf} = \frac{2\mathcal{P}_{T,L}^{k>\mathcal{H}_*}}{\mathcal{P}_T^{k>\mathcal{H}_*}} - 1 \simeq \frac{\alpha\pi H_{inf}^2\sqrt{2\epsilon_{inf}}}{M_P^2}. \tag{16}$$

Here, $H_{inf}^2 \ll M_P^2$, which implies $\Delta\chi_{inf}$ is negligible. However, in a stringy embedding, $\alpha \sim \sqrt{g_{str}}\frac{M_P^2}{M_{10}^2}$, it has been argued in [44] that for the suitable values of the string scale M_{10} and the string coupling g_{str}, we might have $\alpha\frac{H_{inf}^2}{M_P^2} \sim 1$. Thus Eq. (16) may be written as

$$\Delta\chi_{inf} \lesssim \sqrt{\epsilon_{inf}}. \tag{17}$$

We will estimate the chirality parameter $\Delta\chi_{pre\text{-}inf}$ in the pre-inflationary contracting phase. For the inflation, the constant mode (7) is dominated, but for the contraction, $D\int d\eta/z_s^2$ is dominated.

During the contraction, we have

$$\begin{aligned} h_s^{k<\mathcal{H}_*} &\sim \int \frac{d\eta}{a^2[1-\lambda_s\Theta(-\frac{k}{\mathcal{H}})]} \\ &\sim \int \frac{d\eta}{a^2}\left[1+\lambda_s\Theta\left(-\frac{k}{\mathcal{H}}\right)\right], \end{aligned} \tag{18}$$

where $\Theta(-\frac{k}{\mathcal{H}}) \ll 1$ is used since $\Theta < 1$ and the mode is far outside the horizon. Now, with (3) and $\mathcal{H}_* = a_* H_{inf}$, we could obtain

$$\begin{aligned} \Delta\chi_{pre\text{-}inf} &= \frac{2\mathcal{P}_{T,L}^{k<\mathcal{H}_*}}{\mathcal{P}_T^{k<\mathcal{H}_*}} - 1 \\ &\simeq 2\alpha\sqrt{2\epsilon_{pre\text{-}inf}}\frac{H_{inf}^2}{M_P^2}\left(\frac{k}{\mathcal{H}_*}\right)\left(\int^{0-}\frac{d\eta}{a_*^2(1-2\mathcal{H}_*\eta)^3}\right) \\ &\quad\times\left(\int^{0-}\frac{d\eta}{a_*^2(1-2\mathcal{H}_*\eta)}\right)^{-1} \\ &\simeq \alpha\sqrt{2\epsilon_{pre\text{-}inf}}\frac{H_{inf}^2}{M_P^2}\left(\frac{k}{\mathcal{H}_*}\right). \end{aligned} \tag{19}$$

Thus

$$\Delta\chi_{pre\text{-}inf} \sim \frac{\sqrt{\epsilon_{pre\text{-}inf}}}{\sqrt{\epsilon_{inf}}}\left(\frac{k}{\mathcal{H}_*}\right)\Delta\chi_{inf}, \tag{20}$$

which implies that for $k \ll \mathcal{H}_*$, $\Delta\chi_{pre\text{-}inf}$ is negligible, while around cutoff scale, i.e. $k \sim \mathcal{H}_*$, $\Delta\chi_{pre\text{-}inf}$ is far larger than $\Delta\chi_{inf}$.

In slow-roll inflationary scenario, $\Delta\chi$, which reflects the parity violation of primordial GW, is scale invariant, and also negligible.

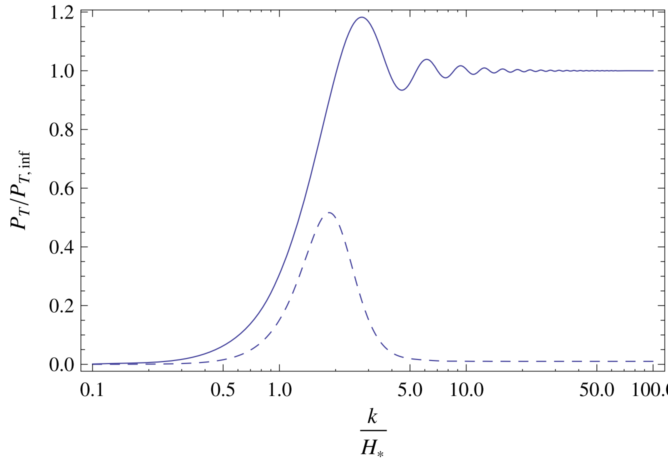

Fig. 1. In bounce inflation, $\mathcal{P}_T$ is plotted (solid line), which for $k > \mathcal{H}_*$ is almost scale-invariant but with a decaying oscillation and for $k < \mathcal{H}_*$ gets a cutoff. The dashed line is $\Delta\chi\mathcal{P}_T$, in which $\Delta\chi$ is the chirality parameter.

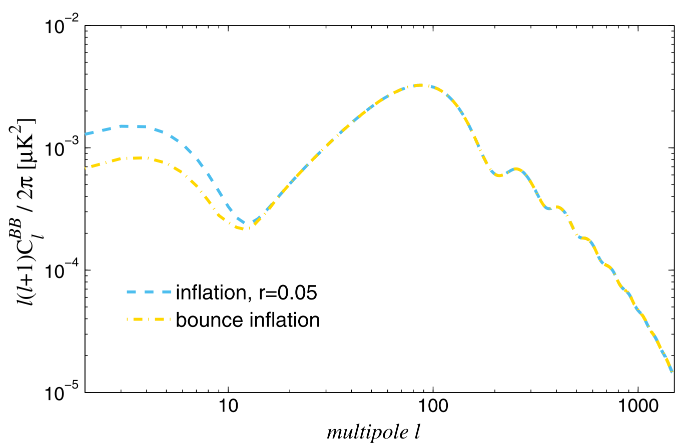

Fig. 2. Theoretical CMB BB-mode power spectrum for the slow-roll inflation model (blue dashed line), in which $r = 0.05$ is set for our simulation, and the inflation model with the pre-inflationary bounce (yellow dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

However, we see that if a pre-inflationary bounce occurs, $\Delta\chi$ will show a bump around the matching scale $k \sim \mathcal{H}_*$, see the dashed line in Fig. 1 for a parameterized $\Delta\chi$ used in Section 3. It could be anticipated that this bump would leave the imprint in TB- and EB-mode power spectrum of CMB at large angular scale. Here, in the leading order of Θ, the polarized GW spectrum $\mathcal{P}_T = \sum_{s=L,R}\mathcal{P}_{T,s}$ is approximately Eq. (12).

3. CMB angular power spectra

3.1. BB-mode power spectrum

In Ref. [11], with the background (3), the primordial scalar spectrum was calculated to fit the Planck + WMAP data. The best-fit values of $\mathcal{H}_*$ and $A_{\mathcal{R},inf}$ are $\ln(\mathcal{H}_*/\mathrm{Mpc}^{-1}) = -8.60$ and $\ln(10^{10}A_{\mathcal{R},inf}) = 3.084$. With this result and Eq. (12), in which $\mathcal{P}_T^{inf}$ is parameterized as

$$\mathcal{P}_{T,inf} = rA_{\mathcal{R},inf}\left(\frac{k}{k_*}\right)^{n_{T,inf}}, \tag{21}$$

we plot the BB-mode power spectrum as Fig. 2 by modifying the CAMB [60], in which $r = 0.05$ is set for our simulation. We see that the large-scale cutoff of the primordial GW spectrum brings a BB-mode power suppression at $l < 20$, which is a significant prediction of pre-inflationary bounce.

3.2. TB- and EB-mode power spectra

The TB- or EB-mode power spectrum is

$$C_l^{T/E,B} \sim \int \frac{dk}{k} \Delta\chi\, \mathcal{P}_T \left[\Delta_l^{T/E}(k)\Delta_l^B(k)\right], \tag{22}$$

which relies on the difference between left-handed h_L and right-handed h_R, i.e. $\Delta\chi\mathcal{P}_T$, e.g. [34,36]. Here, $\Delta\chi$ may be phenomenologically parameterized as

$$|\Delta\chi| = \Delta\chi_{inf} + (\Delta\chi_{pre\text{-}inf} - \Delta\chi_{inf})\left[1/2 - \frac{\mathrm{Tanh}(\frac{1}{B}\mathrm{Log}_{10}\frac{k}{2\mathcal{H}_*})}{2}\right], \tag{23}$$

where for $k > \mathcal{H}_*$, the chiral parameter $\Delta\chi$ equals (16) in slow-roll inflation, and for $k < \mathcal{H}_*$, $\Delta\chi$ equals (19) in the pre-inflationary contraction. We plot $\Delta\chi\mathcal{P}_T$ in Fig. 1, in which since $\Delta\chi \sim \sqrt{\epsilon_{inf}}$ is negligible for $k > \mathcal{H}_*$, while

$$\Delta\chi \sim \left(\frac{k}{\mathcal{H}_*}\right) \tag{24}$$

is large around $k \sim 2\mathcal{H}_*$ but is suppressed for $k \ll \mathcal{H}_*$, a bump appears around $k \sim 2\mathcal{H}_*$.

Usually, the TB- and EB-mode power spectrum should vanish. Here, since the gravity is chiral, the amplitudes of left-handed mode h_L and right-handed mode h_R of the primordial GWs are different, which straightly induce non-vanishing TB- and EB-mode correlations at CMB last scattering surface. We plot TB- and EB-mode correlations in Fig. 3. We can see that compared with those in the slow-roll inflation model, the TB- and EB-mode spectra are enhanced on large scale due to the bump of $\Delta\chi$ at corresponding scale.

The results can be explained as follows. The bump height of the TB- or EB-mode spectrum at $l < 10$ is caused by the reionization of universe, which is mainly depicted by the optical depth to the beginning of reionization, τ. The bump height of the BB- and TB-mode power spectra around $l \sim 2$ have been roughly estimated in Ref. [34], which are

$$C_{l\sim 2}^{BB} \simeq \frac{1}{100}\left(1 - e^{-\tau}\right)^2 C_{T,l\sim 2}^{TT}, \tag{25}$$

$$\left|C_{l\sim 2}^{TB}\right| \simeq \frac{|\Delta\chi|}{10} e^{-\tau}\left(1 - e^{-\tau}\right) C_{T,l\sim 2}^{TT}, \tag{26}$$

where $C_{T,l}^{TT}$ stands for the TT-mode power spectrum from the primordial GW without reionization. Thus since $\mathcal{P}_T$ is cut off on large scale, which lowers $C_{T,l\sim 2}^{TT}$, the reionization bump in the BB-mode power spectrum is suppressed. However, since the TB-mode power spectrum relies on $|\Delta\chi| C_{T,l\sim 2}^{TT}$, if $\Delta\chi_{pre\text{-}inf} \gg \Delta\chi_{inf}$, we may have an enhanced reionization bump, compared with that in slow-roll inflation model.

However, it should be mentioned that for a different set of the values of parameters in Eq. (23), which reflects the details of different bounce mechanisms and different pre-inflationary evolutions, the possibility that $|\Delta\chi|$ does not set off the effect of low $C_{T,l\sim 2}^{TT}$ cannot ruled out, though this case is quite fine-tuning. Thus, whether the reionization bumps of the TB- and EB-mode are enhanced or not might be model-dependent. However, if their reionization bumps are actually enhanced, this will be an interesting signature of the pre-inflationary bounce, different from those in

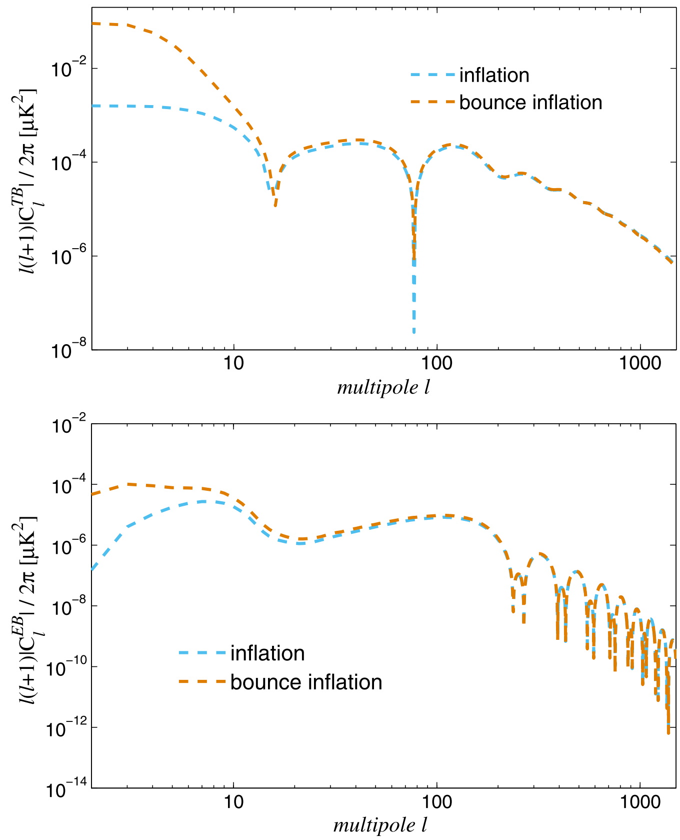

Fig. 3. Theoretical CMB TB- and EB-mode power spectra for the slow-roll inflation model (blue dashed line), in which $r = 0.05$ and $\Delta\chi_{inf} = 0.01$, and the inflation model with the pre-inflationary bounce (brown dashed line), in which $\Delta\chi_{pre\text{-}inf} = 0.5$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the TT-mode power spectrum [11] and the BB-mode power spectrum in Fig. 2.

Finally, we discuss the feasibility to detect this signature of pre-inflationary bounce. Whether the effect of the parity violation is detectable or not is dependent on the value of r. Ref. [36] showed that if $\Delta\chi < 0.5$, the value of r should be larger than 0.22 for Planck and $r > 0.03$ for the CMBPol, see also [34,38]. However, if one consider the cosmic variance limit, it requires $r > 0.008$. Thus the determination of the chirality of primordial GW is quite difficult if r is not large enough. But if $\Delta\chi \sim \pm 1$, the detection will become much easier. In the slow-roll inflation model without pre-inflationary bounce, $\Delta\chi$ is negligible, thus it is hardly possible to detect the signature of parity violation. However, in the model with pre-inflationary bounce, before the inflation begins, $\Delta\chi \sim 1$, which will makes the signature of parity violation on corresponding scales become more detectable. It was found in, e.g., [36] that if $|\Delta\chi| \sim 1$, we only need $r > 0.082$ for Planck, $r > 0.0079$ for CMBPol and $r > 0.0023$ for the cosmic variance limit. Thus the chirality of the primordial gravity might provide us an opportunity to test the pre-inflationary physics.

4. Discussion

Recently, the Planck Collaboration has shown a power deficit in the CMB TT-mode power spectrum at low-l, which might imply the occurrence of a pre-inflationary bounce, a solution to the initial singularity problem of inflationary universe. In string landscape, the bounce will induce a AdS–dS transition [61–63], which is an efficient route to the slow-roll inflation, see the Appendix in [11], also see [64–66] for the effect of perturbation.

The gCS term universally appears in particle physics and string theory [28,29], which will lead to the circular polarization of GW produced in primordial universe. This circular polarization will induce TB- and EB-mode correlations at CMB last scattering surface, which might provide an alternative test for the pre-inflationary bounce.

We have calculated the circularly polarized GW, leaded by the gCS term, in the inflation model with the pre-inflationary bounce, and find that if the pre-inflationary bounce actually occurs, the TB- and EB-mode correlations on large scale will be enhanced, while the BB-mode correlation on corresponding scales is suppressed. This result applies to the cases that the bounce can be realized without modified gravity, e.g. [47–50], and with modified gravity but the parity violation of gravity is mainly from the gravitational CS term.

However, it should be acknowledged that the amplitudes of both TB- and EB-mode correlations are determined by the value of r, thus for negligibly small r both TB- and EB-mode power spectra are actually undetectable, even if $\Delta\chi \simeq 1$. Thus rather than argue whether the detection is possible or not, we would like to conclude that if the gravity in primordial universe is chiral, or parity-violating, compared with those produced during the slow-roll inflation, both TB- and EB-mode correlations around the pre-inflationary bounce may be overwhelmingly enhanced, which is a significant character of the pre-inflationary bounce.

Here, the enhancement of both TB- and EB-mode correlations on large scale actually is a reflection of the background evolution of pre-inflationary universe, since

$$C_{l\sim 2}^{T/E,B} \sim \Delta\chi \sim \sqrt{|\epsilon_{pre\text{-}inf}|}. \tag{27}$$

Thus if the anomalies on large scale in the TT-mode power spectrum is attributed to a pre-inflationary evolution, it is interesting to show TB- and EB-mode power spectra for other non-slow-roll pre-inflationary background, and see whether the result is similar, which will be investigated afterwards. In addition, it is also interesting to consider other sources inducing chiral GW, e.g. non-Abelian gauge fields [67].

Acknowledgements

We thank Mingzhe Li for helpful discussion and comment. This work is supported by NSFC, No. 11222546, and National Basic Research Program of China, No. 2010CB832804. We acknowledge the use of CAMB.

References

[1] P.A.R. Ade, et al., Planck Collaboration, arXiv:1303.5082 [astro-ph.CO].
[2] P.A.R. Ade, et al., Planck Collaboration, arXiv:1303.5083 [astro-ph.CO].
[3] H.K. Eriksen, A.J. Banday, K.M. Gorski, F.K. Hansen, P.B. Lilje, Astrophys. J. 660 (2007) L81, arXiv:astro-ph/0701089.
[4] J. Hoftuft, H.K. Eriksen, A.J. Banday, K.M. Gorski, F.K. Hansen, P.B. Lilje, Astrophys. J. 699 (2009) 985, arXiv:0903.1229 [astro-ph.CO].
[5] A. Rassat, J.-L. Starck, P. Paykari, F. Sureau, J. Bobin, J. Cosmol. Astropart. Phys. 1408 (2014) 006, arXiv:1405.1844 [astro-ph.CO].
[6] Y. Akrami, Y. Fantaye, A. Shafieloo, H.K. Eriksen, F.K. Hansen, A.J. Banday, K.M. Górski, Astrophys. J. 784 (2014) L42, arXiv:1402.0870 [astro-ph.CO].
[7] Y.-S. Piao, B. Feng, X.-m. Zhang, Phys. Rev. D 69 (2004) 103520, arXiv:hep-th/0310206;
Y.-S. Piao, Phys. Rev. D 71 (2005) 087301, arXiv:astro-ph/0502343.
[8] E. Dudas, N. Kitazawa, S.P. Patil, A. Sagnotti, J. Cosmol. Astropart. Phys. 1205 (2012) 012;
C. Condeescu, E. Dudas, J. Cosmol. Astropart. Phys. 1308 (2013) 013.
[9] F.T. Falciano, M. Lilley, P. Peter, Phys. Rev. D 77 (2008) 083513, arXiv:0802.1196 [gr-qc];
M. Lilley, L. Lorenz, S. Clesse, J. Cosmol. Astropart. Phys. 1106 (2011) 004, arXiv:1104.3494 [gr-qc].
[10] J. Mielczarek, J. Cosmol. Astropart. Phys. 0811 (2008) 011, arXiv:0807.0712 [gr-qc];
J. Mielczarek, M. Kamionka, A. Kurek, M. Szydlowski, J. Cosmol. Astropart. Phys. 1007 (2010) 004, arXiv:1005.0814 [gr-qc].
[11] Z.G. Liu, Z.K. Guo, Y.S. Piao, Phys. Rev. D 88 (2013) 063539, arXiv:1304.6527.
[12] T. Qiu, arXiv:1404.3060 [gr-qc].
[13] Z.G. Liu, Z.K. Guo, Y.S. Piao, Eur. Phys. J. C 74 (2014) 3006, arXiv:1311.1599 [astro-ph.CO].
[14] T. Biswas, A. Mazumdar, arXiv:1304.3648 [hep-th].
[15] P. Labrana, arXiv:1312.6877 [astro-ph.CO].
[16] Z.G. Liu, H. Li, Y.S. Piao, arXiv:1405.1188 [astro-ph.CO].
[17] G.F.R. Ellis, R. Maartens, Class. Quantum Gravity 21 (2004) 223.
[18] E. Ramirez, D.J. Schwarz, Phys. Rev. D 85 (2012) 103516, arXiv:1111.7131 [astro-ph.CO].
[19] M. Cicoli, S. Downes, B. Dutta, F.G. Pedro, A. Westphal, arXiv:1407.1048 [hep-th].
[20] C.R. Contaldi, M. Peloso, L. Kofman, A.D. Linde, J. Cosmol. Astropart. Phys. 0307 (2003) 002, arXiv:astro-ph/0303636.
[21] J.M. Cline, P. Crotty, J. Lesgourgues, J. Cosmol. Astropart. Phys. 0309 (2003) 010, arXiv:astro-ph/0304558.
[22] N. Kitazawa, A. Sagnotti, J. Cosmol. Astropart. Phys. 1404 (2014) 017, arXiv:1402.1418 [hep-th].
[23] M. Cicoli, S. Downes, B. Dutta, arXiv:1309.3412 [hep-th].
[24] F.G. Pedro, A. Westphal, arXiv:1309.3413 [hep-th].
[25] Y.-S. Piao, S. Tsujikawa, X.-m. Zhang, Class. Quantum Gravity 21 (2004) 4455, arXiv:hep-th/0312139.
[26] U. Seljak, M. Zaldarriaga, Phys. Rev. Lett. 78 (1997) 2054, arXiv:astro-ph/9609169.
[27] M. Kamionkowski, A. Kosowsky, A. Stebbins, Phys. Rev. Lett. 78 (1997) 2058, arXiv:astro-ph/9609132.
[28] L. Alvarez-Gaume, E. Witten, Nucl. Phys. B 234 (1984) 269.
[29] R. Jackiw, S.Y. Pi, Phys. Rev. D 68 (2003) 104012, arXiv:gr-qc/0308071.
[30] S. Alexander, N. Yunes, Phys. Rep. 480 (2009) 1, arXiv:0907.2562 [hep-th].
[31] A. Lue, L.M. Wang, M. Kamionkowski, Phys. Rev. Lett. 83 (1999) 1506, arXiv:astro-ph/9812088.
[32] K. Choi, J.c. Hwang, K.W. Hwang, Phys. Rev. D 61 (2000) 084026, arXiv:hep-ph/9907244.
[33] S.H.S. Alexander, M.E. Peskin, M.M. Sheikh-Jabbari, Phys. Rev. Lett. 96 (2006) 081301, arXiv:hep-th/0403069.
[34] S. Saito, K. Ichiki, A. Taruya, J. Cosmol. Astropart. Phys. 0709 (2007) 002, arXiv:0705.3701 [astro-ph].
[35] M. Li, Y.F. Cai, X. Wang, X. Zhang, Phys. Lett. B 680 (2009) 118, arXiv:0907.5159 [hep-ph].
[36] V. Gluscevic, M. Kamionkowski, Phys. Rev. D 81 (2010) 123529, arXiv:1002.1308 [astro-ph.CO].
[37] J.-Q. Xia, J. Cosmol. Astropart. Phys. 0709 (2012) 046, arXiv:1201.4457 [astro-ph.CO].
[38] A. Wang, Q. Wu, W. Zhao, T. Zhu, Phys. Rev. D 87 (2013) 103512, arXiv:1208.5490v3 [astro-ph].
[39] B. Feng, M. Li, J.Q. Xia, X. Chen, X. Zhang, Phys. Rev. Lett. 96 (2006) 221302, arXiv:astro-ph/0601095.
[40] G.C. Liu, S. Lee, K.W. Ng, Phys. Rev. Lett. 97 (2006) 161303, arXiv:astro-ph/0606248.
[41] P. Cabella, P. Natoli, J. Silk, Phys. Rev. D 76 (2007) 123014, arXiv:0705.0810 [astro-ph].
[42] M. Li, X. Zhang, Phys. Rev. D 78 (2008) 103516, arXiv:0810.0403 [astro-ph].
[43] S.Y. Li, J.Q. Xia, M. Li, H. Li, X. Zhang, arXiv:1405.5637 [astro-ph.CO].
[44] S. Alexander, J. Martin, Phys. Rev. D 71 (2005) 063526, arXiv:hep-th/0410230.
[45] D.H. Lyth, C. Quimbay, Y. Rodriguez, J. High Energy Phys. 0503 (2005) 016, arXiv:hep-th/0501153.
[46] M. Satoh, S. Kanno, J. Soda, Phys. Rev. D 77 (2008) 023526, arXiv:0706.3585 [astro-ph].
[47] T. Qiu, J. Evslin, Y.-F. Cai, M. Li, X. Zhang, J. Cosmol. Astropart. Phys. 1110 (2011) 036, arXiv:1108.0593 [hep-th];
T. Qiu, X. Gao, E.N. Saridakis, Phys. Rev. D 88 (2013) 043525, arXiv:1303.2372 [astro-ph.CO].
[48] D.A. Easson, I. Sawicki, A. Vikman, J. Cosmol. Astropart. Phys. 1111 (2011) 021, arXiv:1109.1047 [hep-th].
[49] M. Osipov, V. Rubakov, J. Cosmol. Astropart. Phys. 1311 (2013) 031, arXiv:1303.1221 [hep-th].
[50] M. Koehn, J.-L. Lehners, B.A. Ovrut, arXiv:1310.7577 [hep-th].
[51] K. Bamba, A.N. Makarenko, A.N. Myagky, S. Nojiri, S.D. Odintsov, J. Cosmol. Astropart. Phys. 1401 (2014) 008, arXiv:1309.3748 [hep-th];
K. Bamba, A.N. Makarenko, A.N. Myagky, S.D. Odintsov, Phys. Lett. B 732 (2014) 349, arXiv:1403.3242 [hep-th].
[52] T. Biswas, A. Mazumdar, W. Siegel, J. Cosmol. Astropart. Phys. 0603 (2006) 009, arXiv:hep-th/0508194;
T. Biswas, E. Gerwick, T. Koivisto, A. Mazumdar, Phys. Rev. Lett. 108 (2012) 031101, arXiv:1110.5249 [gr-qc];
T. Biswas, A.S. Koshelev, A. Mazumdar, S.Y. Vernov, J. Cosmol. Astropart. Phys. 1208 (2012) 024, arXiv:1206.6374 [astro-ph.CO].

[53] G. Calcagni, J. High Energy Phys. 1003 (2010) 120, arXiv:1001.0571 [hep-th];
G. Calcagni, J. Cosmol. Astropart. Phys. 1312 (2013) 041, arXiv:1307.6382 [hep-th].
[54] D. Battefeld, P. Peter, arXiv:1406.2790 [astro-ph.CO].
[55] J.-L. Lehners, Class. Quantum Gravity 28 (2011) 204004, arXiv:1106.0172 [hep-th].
[56] L. Battarra, M. Koehn, J.L. Lehners, B.A. Ovrut, J. Cosmol. Astropart. Phys. 1407 (2014) 007, arXiv:1404.5067 [hep-th].
[57] J. Liu, Y.-F. Cai, H. Li, J. Theor. Phys. 1 (2012) 1, arXiv:1009.3372 [astro-ph.CO];
J.Q. Xia, Y.F. Cai, H. Li, X. Zhang, Phys. Rev. Lett. 112 (2014) 251301, arXiv:1403.7623 [astro-ph.CO].
[58] M. Gasperini, G. Veneziano, Astropart. Phys. 1 (1993) 317.
[59] M. Gasperini, G. Veneziano, Phys. Rep. 373 (2003) 1.
[60] A. Lewis, A. Challinor, A. Lasenby, Astrophys. J. 538 (2000) 473, arXiv:astro-ph/9911177;
A. Challinor, A. Lewis, Phys. Rev. D 71 (2005) 103010, arXiv:astro-ph/0502425.
[61] Y.-S. Piao, Phys. Rev. D 70 (2004) 101302, arXiv:hep-th/0407258.
[62] J. Garriga, A. Vilenkin, J. Zhang, J. Cosmol. Astropart. Phys. 1311 (2013) 055, arXiv:1309.2847 [hep-th].
[63] B. Gupt, P. Singh, arXiv:1309.2732 [hep-th].
[64] Y.S. Piao, Phys. Lett. B 677 (2009) 1, arXiv:0901.2644 [gr-qc].
[65] Z.G. Liu, Y.S. Piao, Class. Quantum Gravity 31 (2014) 175004, arXiv:1404.5748 [hep-th].
[66] J. Zhang, Z.G. Liu, Y.S. Piao, Phys. Rev. D 82 (2010) 123505, arXiv:1007.2498 [hep-th].
[67] A. Maleknejad, M. Noorbala, M.M. Sheikh-Jabbari, arXiv:1208.2807 [hep-th];
A. Maleknejad, Phys. Rev. D 90 (2014) 023542, arXiv:1401.7628 [hep-th].